LA-UR -87-3094

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LA-UR--87-3094

DE88 000519

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SUBMITTED TO: Proceedings of "Physics with Light Mesons", August 14, 1987, Los Alamos National Laboratory, Los Alamos, NM 87545

PRODUCTION AND PROPAGATION OF MESONS IN COMPLEX NUCLEI

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ABSTRACT

The propagation of unstable mesons in nuclei is considered with regard to the use of the nucleus as a micro-laboratory. Specific problems considered are those of the η and the S^*/δ systems.

INTRODUCTION

The use of the nucleus as a micro-laboratory is not a new idea. Indeed the propagation of mesons, after electromagnetic production, was used to determine the ρ-nucleon interaction[1], the ϕ-nucleon interaction[2] [obtaining $\sigma(\phi N)=8.8$ mb. in agreement with the vector dominance determination from photoproduction of $\sigma(\phi N)=8.3$ mb.[3] and the additive quark model prediction of 13 mb.], and the η-nucleon interaction[4] at high energies. There are many ways to go about this process and there have been two fairly recent discussions of the problem in conferences, one a little over two years ago in Tempe[5] and one a year ago last march at the Mainz meeting[6]. There has been at least one calculation of the propagation of unstable hyperons in nuclei[7].

One possible technique is the use of a specific nuclear transition in the exclusive production of mesons to act as a filter to separate the various types of mesons which are so abundant around 1 GeV. I will not discuss this method although I know that Dick Jacob (e.g.) has done work in this area.

What I will talk about are some new results relating to the questions of η and "S^*" propagation.

The experiments on η production are on-going at LAMPF and we will address the question of how some of the data might be analyzed to learn something about the η propagation in nuclei. A second technique, using polarized nuclear targets, will also be discussed with a view to determining the total cross section of the η (and possibly other mesons) scattering from nucleon targets.

There has been much interest lately in the structure of the two mesons (traditionally called S^* and δ) which are relatively narrow and lie at the $K\bar{K}$ threshold. If these mesons are quasi molecular bound states of two kaons then they will not be described by the quark model and should not fit into a simple $q\bar{q}$ scheme. This question of the structure of these mesons has fundamental implications for our understanding of hadronic physics

η PRODUCTION AND PROPAGATION

Since the energy of accelerators is finite, and is often the limiting factor in experiments, the production on nuclei is often done at, or near, the nuclear threshold, i.e., below the threshold for production on the proton. While one might think that this complicates the production process it is often an advantage in sorting out what has actually happened. At threshold the produced meson is moving very much along the original beam direction so that it forms a secondary beam. This type of production is often refered to as production from, or off-of, the Fermi motion. One may note that, if the Fermi momentum is thought of as extending to infinite values (with vanishing probability of course) then, it would be possible to produce mesons with very low energy beams and one would have a wonderful energy-producing device. We know that this doesn't happen and it is worthwhile to discuss for a moment how it works.

If one had a beam incident on an excited nucleus such a reaction would be possible. The nucleon in the nucleus would be de-excited and the external system would gain the energy. What prevents this from happening in the usual case is that all of the nucleons in the nucleus are already in their lowest state so that the nucleon that is struck in the production process must end up with no less energy than it started with. This is just a classical statement of Pauli blocking. Table I shows the kinematics for production at zero degrees for various incident pion momenta with minimum Fermi momenta required. The initial and final kinetic energies of the nucleon are also shown. When the final energy is equal to the initial one, the absolute threshold has been reached for meson production on a heavy nucleus.

Incident Momentum (MeV/c)	Fermi Momentum (MeV/c)	Kinetic Energies (MeV) Initial Nucleon	Final Nucleon	Final Meson
520	255	35	15	9
540	220	26	22	13
560	186	19	30	17
580	154	13	39	22
600	122	8	48	28
620	92	5	59	34
640	63	2	71	40
660	35	1	83	47
680	7	0	96	54
700	19	0	110	61

Table I

Kinematics for 0° to 0° production from the Fermi momentum required to allow η production. The allowed "subthreshold" region is between the two horizontal lines where the final nucleon kinetic energy is greater than the initial but there is some Fermi momentum required.

Such a system has been modeled in the form of an intranuclear cascade code computed along strictly classical lines. Here the nucleons move in a potential well (with binding energies which correspond to various shells) and suffer collisions governed by a distance of approach compared to a total cross section. These nucleon collisions are "Pauli blocked" as well, of course, otherwise the nucleus would give up its energy to a few escaping nucleons with the rest being tightly bound in the s-state. With this motion occuring we send a pion into the system and ask what happens based on our knowledge of classical (on-shell) cross sections. Various types of interaction are permitted in different versions of the computer code. For the η production we have pion elastic scattering, π-2π and π-3π reactions, pion absorption and of course, η production. It is also necessary to include η-nucleon reactions, that is in fact one of the interests in the problem. We note that the reaction η-nucleon $\to$ π-nucleon certainly exists and we know those cross sections from detailed balance. This later cross section is exothermic so it has no threshold and tends to infinity for zero η-nucleon momentum. In fact these cross sections can be represented approximately at threshold by:

$$\sigma(\pi^- p \to \eta n) = C\, p_\eta / p_\pi$$

and

$$\sigma(\eta n \to \pi^- p) = C\, p_\pi / p_\eta$$

where the momenta are in the meson-nucleon center of mass system. The value of "C" depends on the data base chosen. If one uses the bulk of the data in the HERA report[8] then C=6 mb.. However there is recent data (also in this same report) by Brown *et al.*[9], presumed to be more accurate than the older values, which lead to C=4.38 mb.. A recent value from LAMPF measurements by Peng *et al.*[10] tends to agree with the older value and supports C=6. The code uses one of these cross sections near threshold but has a data base for other energies which is less ambiguous. The η-nucleon elastic scattering cross section is essentially unmeasured. From models including pion scattering and the π-η reaction, elastic η-nucleon can be calculated and Bhalerao and Liu[11] obtain a scattering length of .28+.19i fm, which would lead to a zero energy elastic scattering cross section of about 10 mb. In another analysis Tuan[12] obtained a scattering length of .82 fm, which would lead to an elastic scattering cross section of 84 mb. at zero energy. These are to be compared with the value of total cross section of ~20 mb. given by the additive quark model and the high energy production[4].

The elastic scattering can have a large influence on the nuclear system, however, since the η will lose energy in each scattering. This has the effect of shifting the spectrum of ηs toward lower energies. Note that, at these lower energies, the cross section for converting back to pions is greater so that the net effect is to cause more of the reconversion process to occur as well as to deplete the upper end of the spectrum. These secondary pions are of interest in themselves. Note that the ηs will have low energy and momentum and the Fermi momentum of the nucleon with which they interact will be of the same order. For this reason the pions produced in this manner will be nearly isotropic and of high energy (having the bulk of the η mass as kinetic energy). Another feature of these pions is they will be produced in equal numbers (on an isospin zero nucleus) for all three charges. Thus if one looks for pions of opposite charge to the incident pion (i.e., double charge exchange) at back angles and high energies these pions can be picked out. This gives a direct measure of the process π-η-π.

We now present calculations of this process modeled with the INC code mentioned earlier. Figure 1 shows the spectrum of ηs measured by Peng *et al.*, at LAMPF on ^{12}C. The histogram shows the result of the calculation for no elastic η scattering. There are two striking features to be seen:

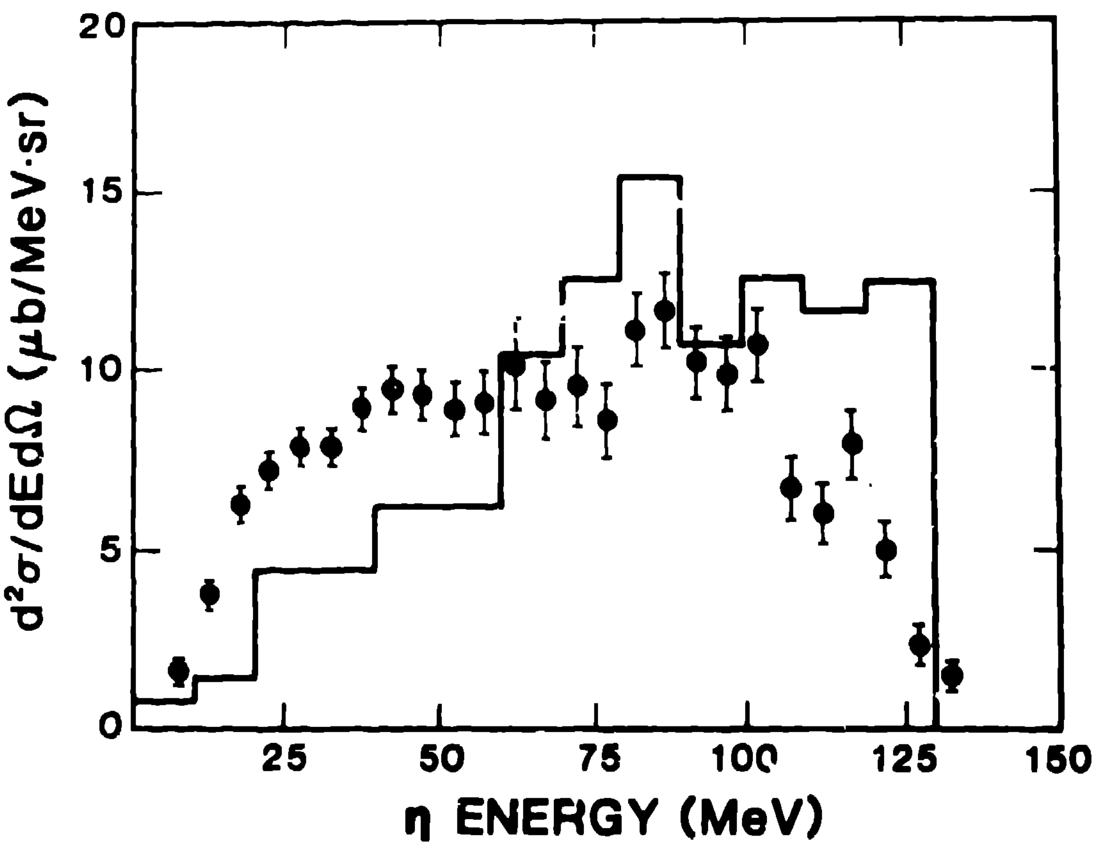

Figure 1. Comparison of the calculated η spectrum (histogram) with the data of Peng *et al.*[10,13] for incident pion momentum of 680 MeV/c on ^{12}C. The calculation has no elastic η scattering.

First the magnitude is very good. It is not unusual to be wrong by a factor of 5 or more in the calculation of exclusive cross sections of this type. As seen the inclusive prediction does quite well

Secondlv the shape leaves something to be desired. There are two few events predicted in the low energy region. The ηs produced in that region have low energy and hence are subject to the inverse reaction η-nucleon goes to π-nucleon.

Peng has determined the inelastic cross section from the A dependence[13] and finds a value of ~20 mb. Figure 2 shows a histogram of the reaction cross sections observed in the calculation. As seen, the average value is around 25 mb, so the A dependence seen bv Peng will be well represented.

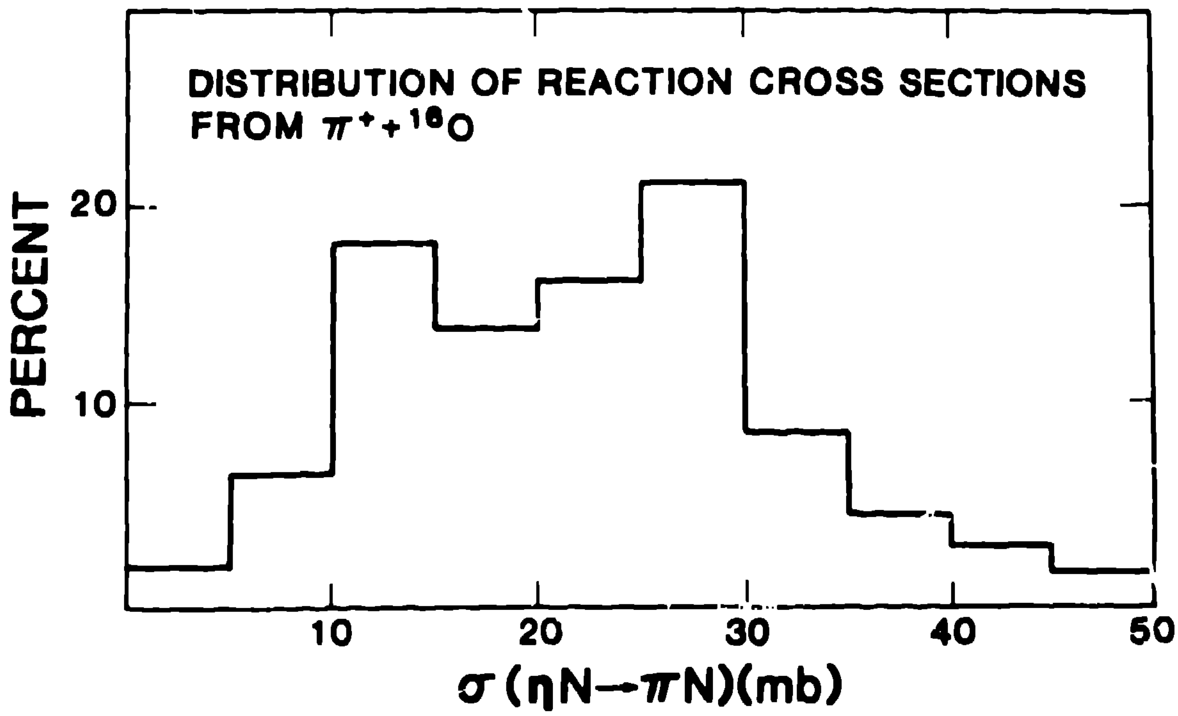

Figure 2. Histogram of the percentage of inverse reaction cross sections ($\eta N \rightarrow \pi N$) observed in the calculation.

That still leaves us with a lack of ηs in the low energy region. One might well believe that the introduction of an η-nucleon elastic cross section would help the situation by moving the high energy ηs to the lower energy portion of the spectrum, but Figure 3 shows that the inclusion of a constant cross section of 20 mb. only lowers the entire curve. The low energy ηs scatter as well and lowering their energy gives them a much larger reaction cross section.

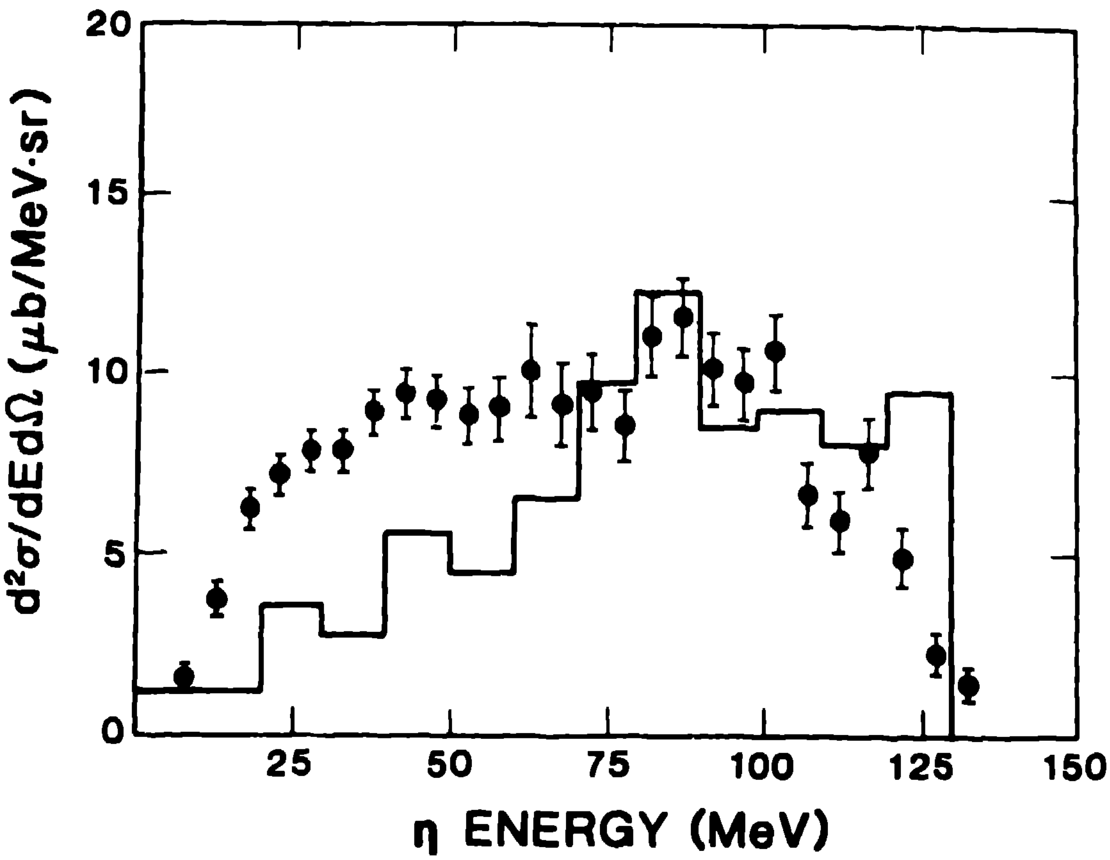

Figure 3. Comparison of the calculated η spectrum with the data[10,13] for an η-Nucleon elastic scattering cross section of 20 mb. The parameters are the same as Fig. 1.

Figure 4 shows the pions obtained from the π-η-π reaction superposed on the π-π^0-π background. As can be seen it is quite possible to separate these pions kinematically from the others. This gives us a direct measure of the reaction of ηs with nucleons.

Another method of obtaining information about unstable particle interactions involves the use of polarized targets[14]. If one takes a certain class of nuclei (^{10}B is the classic example with its 3^+ ground state) and selects the m-states (the ideal case would be to have only the m = +2 occupied) and then produces with a π^+ beam (say) an η going to the ground state of ^{10}C then one finds that the left-right asymmetry tends to vanish. First of all (under rather reasonable shell model approximations) it must vanish in the absence of distortion of the incoming and outgoing waves. In fact these distortions generally tend to cancel so that if one had the same incident and final momenta and the same distortions then again

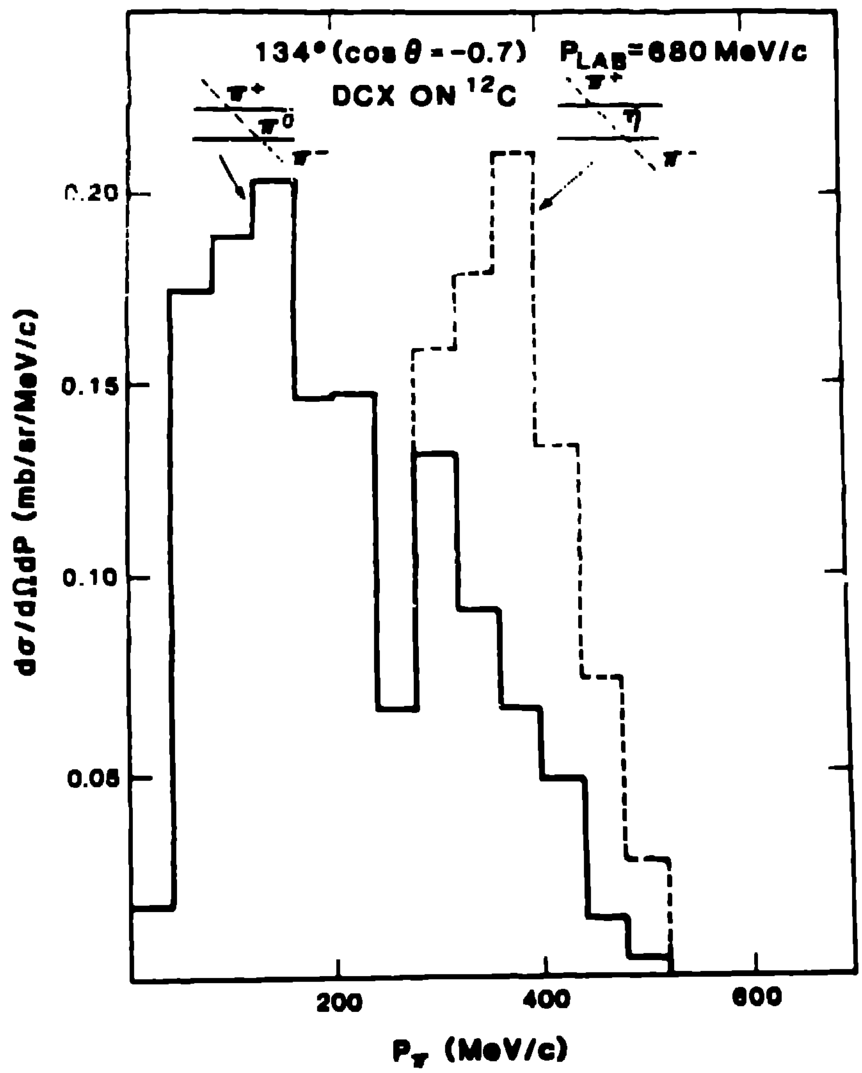

Figure 4. Contributions to the double charge exchange spectrum at 134° from the two mechanisms involving either an intermediate π° or η.

there would be no asymmetry. The idea is that one can measure the interaction of the pion directly (beams are available) and then compare the distortion of the pion and η by the polarization measurement and hence infer the interaction of the η for which beams are <u>not</u> available.

Figure 5 shows the calculation of the polarisation expected for a rather small value of the elastic cross section with no inverse η-π reaction present. This is only a preliminary study to establish the principle and further studies are needed to find what accuracy can be expected with this method.

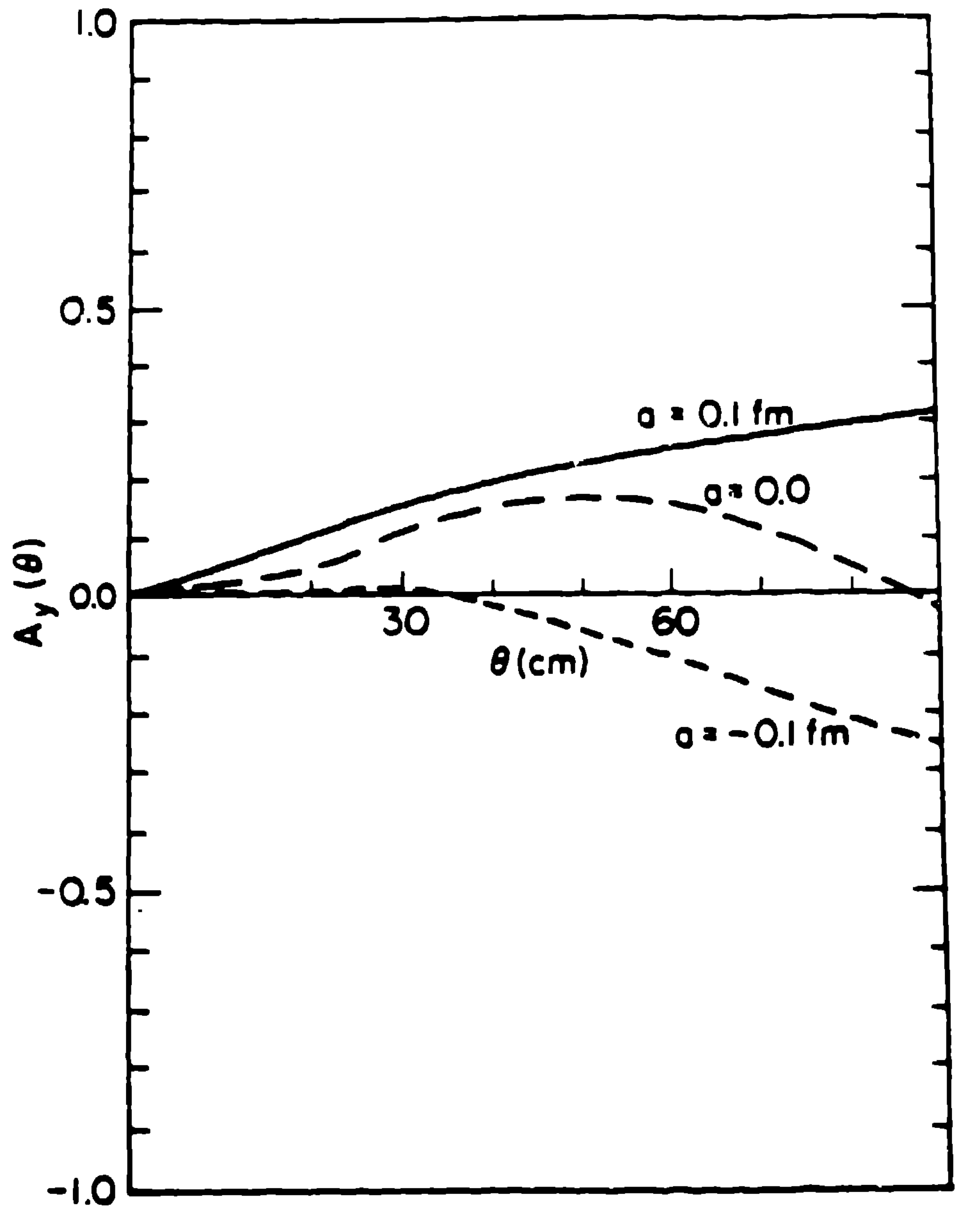

Figure 5. Asymmetry in the reaction $^{10}B(\pi^+,\eta)^{10}C$ with the target in the M = +2 substate. The pion energy is 460 MeV.

The S^*/δ Problem

There has been considerable interest lately in the structure of the S^* and δ mesons[15,16]. These two objects lie essentially at the K-$\bar{K}$ threshold and there is a distinct possibility that they are the I=0 and I=1 combinations of these two mesons in a molecular bound state or in a low-lying resonance. If so, their structure is completely different from a $q\bar{q}$ state and one would not expect to find them in a quark model description. One possible method for the investigation of this possibility is to produce them in a nucleus, since their propagation through the nuclear medium should be very different according to the various possibilities.[2]

Lenz[2] and Alexandrou and Sato[17] consider $S^*(\delta)$ production with pion beams having momenta of the order of 3 GeV/c. Reference 17 considers three models: the S^* is

a) part of the $q\text{-}\bar{q}$ L=1 nonet (σ_{inel} = 18-20 mb.)

b) a member of the lightest $q^2\bar{q}^2$ nonet (σ_{inel} = 27.5 mb.)

c) a $K\bar{K}$ molecule (σ_{inel} = 41 mb.).

For the inclusive production cross section as a function of A (Fig 6) these different cases are somewhat distinguishable; certainly the $q\bar{q}$ from the others.

Also considered was the exclusive production to a specific nuclear state+S^*+proton. These cross sections as a function of A (Fig. 7) also show a clear separation of the 2-body and 4-body cross sections. These methods rely on the ability to calculate an inelastic cross section from the quark structure. This is a reasonable assumption normally but could be wrong due to, e.g., a resonance in the S^*-N interaction.

Another experiment considered in Ref. 17, which addresses more directly the possibility of determining the structure, is the energy dependence in the region of a wide K^--N resonance around K^- momentum of 1 GeV/c (2 GeV/c S^* momentum). This resonance would lead to a minimum in the production cross section as shown in Figure 8 as a function of S^* momentum. Note that one has yet to fold in the Fermi momentum of the production process. The effect is disappointingly small and could be masked by a variation in the $q\bar{q}$ S^*-N cross section. One can not use a narrow resonance for this purpose (it would be broadened by the Fermi motion anyway) and the wide one does not show enough variation (as seen already in the K^--nucleus total cross section shown in Figure 9).

These techniques for observing the molecular state rely on the fact that the K^- has a stronger interaction with the nucleon than the average meson. Let me now describe a technique that does not necessarily rely on an absolute measurement or the use of a total cross section. It depends on the fact that the interactions of the K^+ and K^- with nucleons is very different. The measurement of the relative numbers of K^-/K^+ seen from S^* production gives a direct measure of the structure of the system. If the S^* (or δ) leaves intact from the nucleus then equal numbers of K^+ and K^- will be observed from the decay S^* $(\delta) \rightarrow K^+K^-$. In contrast to a tightly bound system such as a $q\bar{q}$ however, a loosely bound "molecular" S^* or δ is <u>very unlikely to emerge from a nucleus</u>. In propagating through the nucleus the K^- member of the pair has a high probability of annihilation through the reaction $K^-p \rightarrow \pi^\circ\Lambda$. Because of the light binding of the K^+K^- "molecule" the K^+ acts as a spectator during the K^- annihilation and will continue to propagate with (essentially) the same direction and speed as the original S^*.

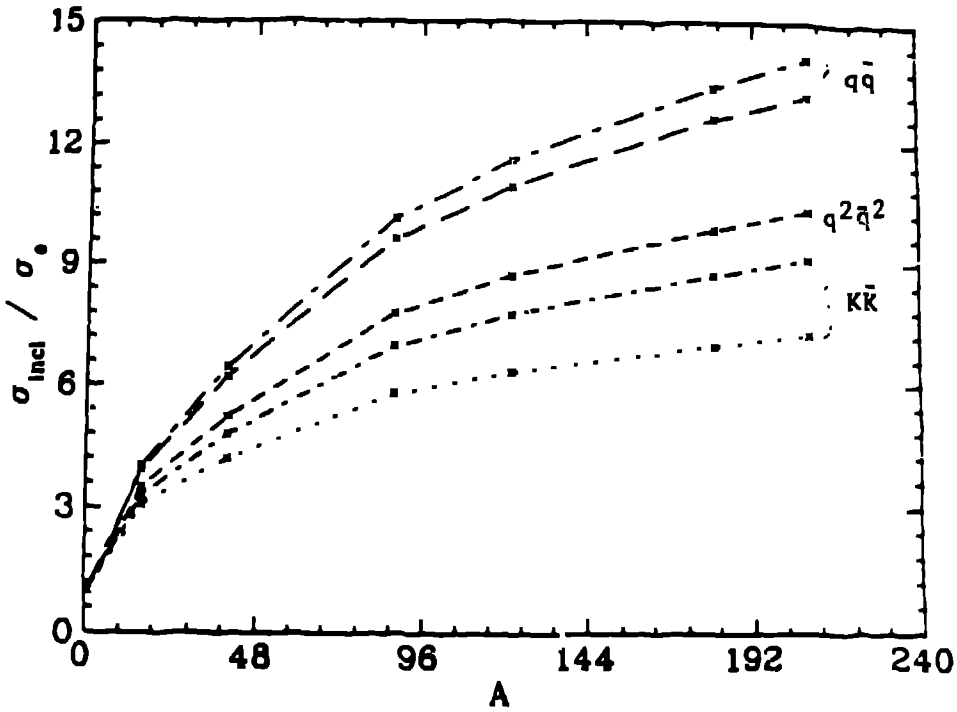

Figure 6. The A-dependence of the inclusive production cross section for the three models considered by Ref. 17.

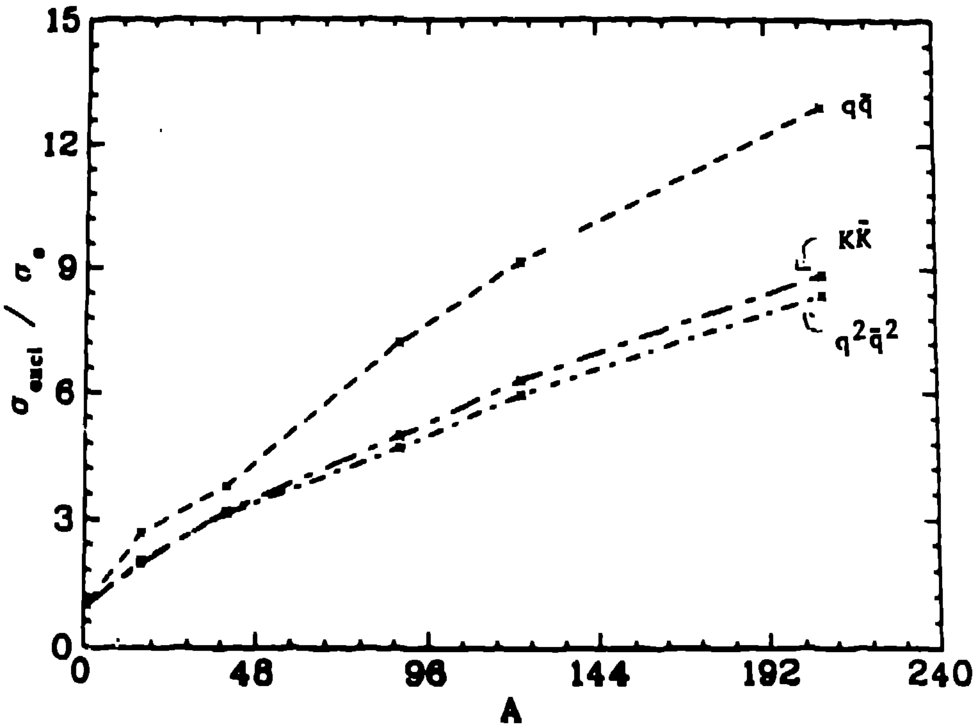

Figure 7. Exclusive cross sections as a function of A of a reaction in which one detects an S^* and proton in coincidence leading to a definite final state of the residual nucleus (from Ref. 17).

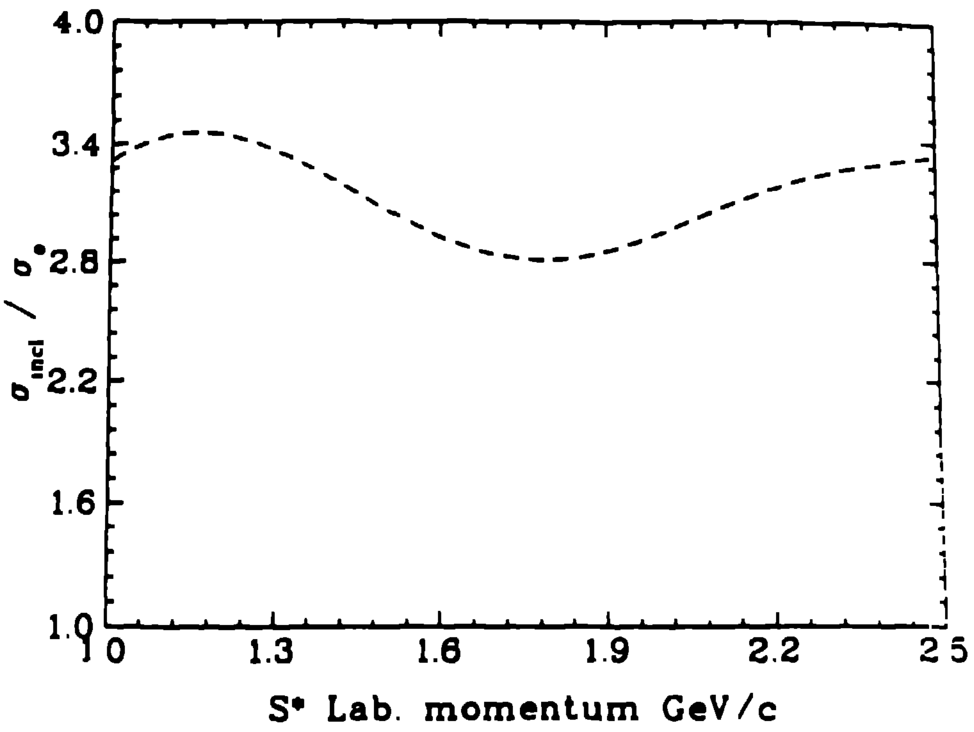

Figure 8. Inclusive S^* production cross section as a function S^* momentum showing the effect of a K^--Nucleon resonance on the quasi-molecular model (from Ref. 17).

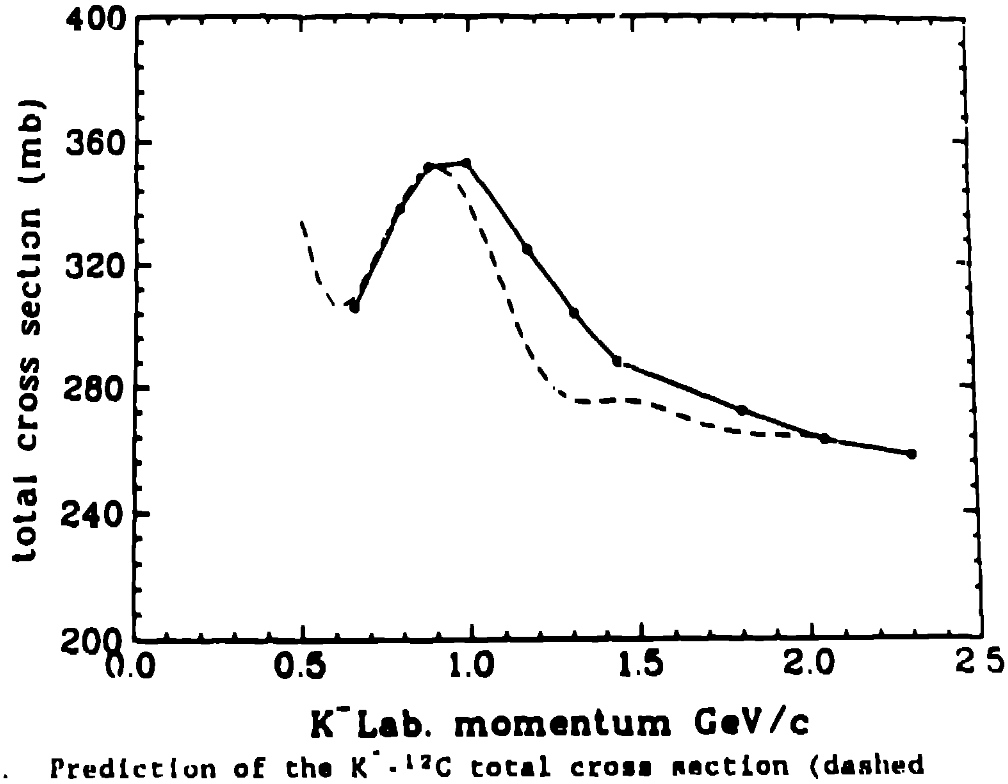

Figure 9. Prediction of the K^--^{12}C total cross section (dashed line) compared with data showing that the Fermi averaging can be done sufficiently well (from Ref. 17).

A measurement of the K^+ spectrum from this process would give a direct measure of the motion of the parent S^* (or δ) molecule, slightly broadened by the small K^+N elastic scattering. Figure 10 shows a comparison of the K^+p total cross section (=elastic cross section) and the K^-p total cross section. Note that the $K^-+p \to \pi^0+\Lambda$ process (most of the K^-p total cross section) is exothermic and is essentially one-way, i.e. the Λ is not likely to produce a K^- again since $\Lambda+n \to K^-+p+n$ requires a substantial amount of energy.

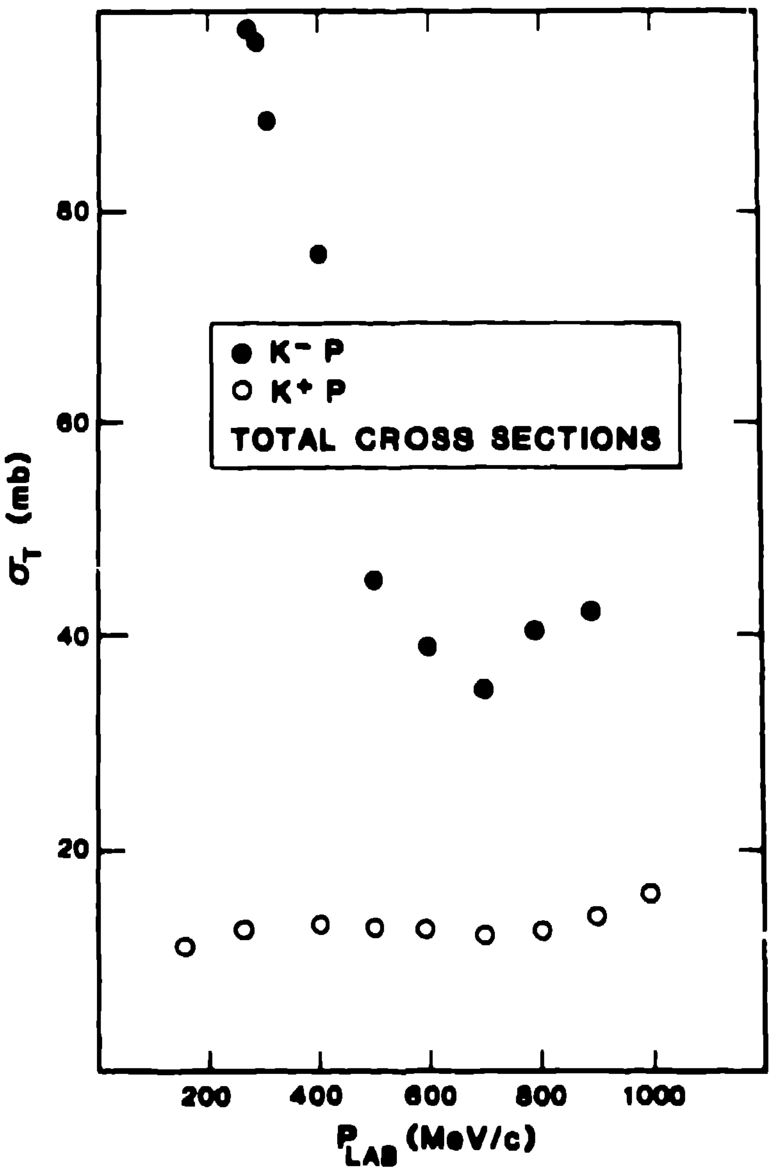

Figure 10. Comparison of the K^-p and K^+p total cross sections.

The problem is to know, for any given K^+ or K^- that it came from an S^*. Here is where the knowledge of the kinematics at threshold comes to our aid.

Incident Momentum (MeV/c)	Fermi Momentum (MeV/c)	Kinetic Energies (MeV) Initial Nucleon	Final Nucleon	Final Meson
1000	392	82	46	48
1040	353	66	59	61
1080	316	53	73	75
1120	280	42	89	90
1160	246	32	105	106
1200	214	24	122	122
1240	183	18	140	139
1280	152	12	160	157
1320	123	8	180	175
1360	95	5	201	194
1400	68	2	223	213
1440	42	1	245	233
1480	16	0	269	253
1520	-9	0	293	274
1560	-33	1	318	294

Table II

Kinematics for nuclear production of a generic meson of S^*/δ type.

Table II shows the kinematics for S^* production in the same format as Table I. One sees that the S^* is produced with a kinetic energy around 120 MeV in this nuclear reaction for an incident momentum of 1.2 GeV/c. Thus each kaon will have about 1/2 of this energy and both kaons will be moving along the beam axis.

Figure 11 shows the distribution of K^+s, and K^- along the beam axis. As can be seen there remains a clear signal for the K^+s coming from S^* decay.

One possible experiment is simply to measure the K^- spectrum in this region and rely on the calculation to get the number of S^*s produced. If one sees a distribution of K^-s that looks like the free-space K^- distribution then it is apparent that the S^* is a $q\bar{q}$ meson, at least for the time that it spends in the nucleus. If one sees the K^- spectrum strongly depleted relative to that predicted by the code then the interpretaion is not unique. It may be that there is a quasi-molecular state with the K^- partner converted to Λ, but it may be also (especially in the case of the $q^2\bar{q}^2$ state where the inelastic cross section is around 40 mb.) that the reaction $S^*+p \to K^+ + \Lambda$ is strong and the S^*s (and hence the K^-s) are depleted in this way. The K^+s comming from this reaction have an energy different from the K^+s arising from the decay of the S^*s however.

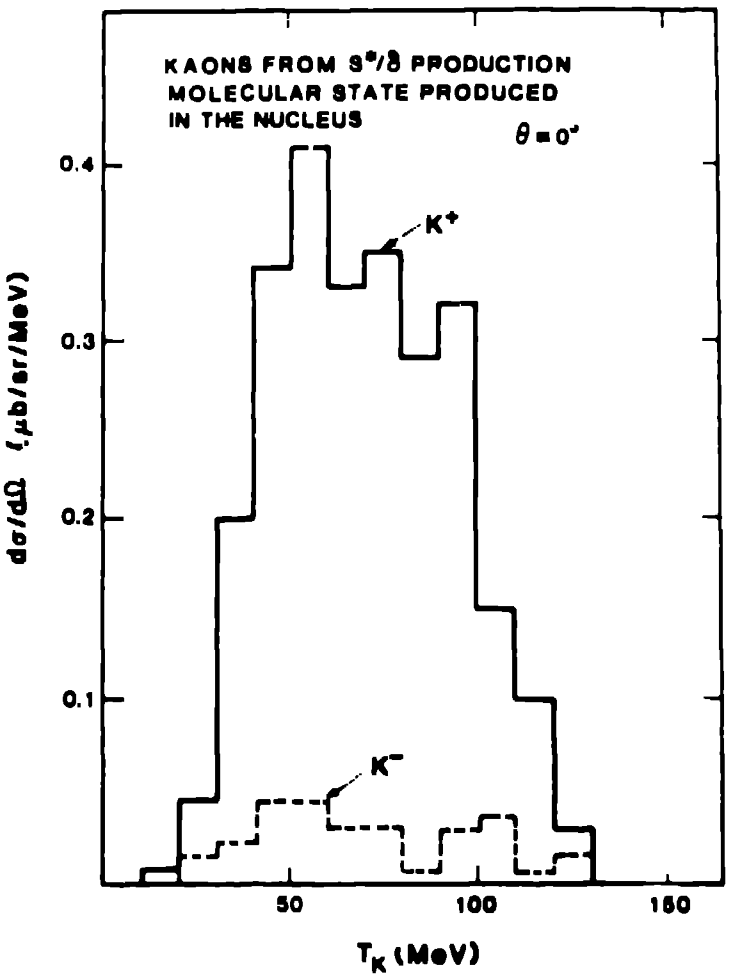

Figure 11. Comparison of the K^+ and K^- spectra for the case of the quasi-molecular model.

A better experiment is the detection of both the K^+s and the K^-s (not in coincidence). If one sees that the number of K^+s in the S^* decay region is much greater than the number of corresponding K^-s then the molecular hypothesis is greatly favored. If both are equally depleted (relative to the prediction of the code) the $q^2\bar{q}^2$ picture is likely to be right. While this second measurement is much better from the point of view of information content, it is more difficult since the K^+s from the S^* decay must be distinguished from the general K^+ background. To get an estimate of this background problem we consider the reaction $\pi^+ + n \to K^+ + \Lambda$ (the reactions $\pi^+ + n \to K^+ + \Sigma^0$ and $\pi^+ + p \to K^+ + \Sigma^+$ will give smaller but similar contributions). Figure 12 shows how the peak in the K^+ spectrum sits on this background. Clearly it is discernable but will require a careful experiment since one is measuring low energy kaons at zero degrees. The use of a π^- beam eliminates the Λ reaction (but not the Σ) and should lower the background.

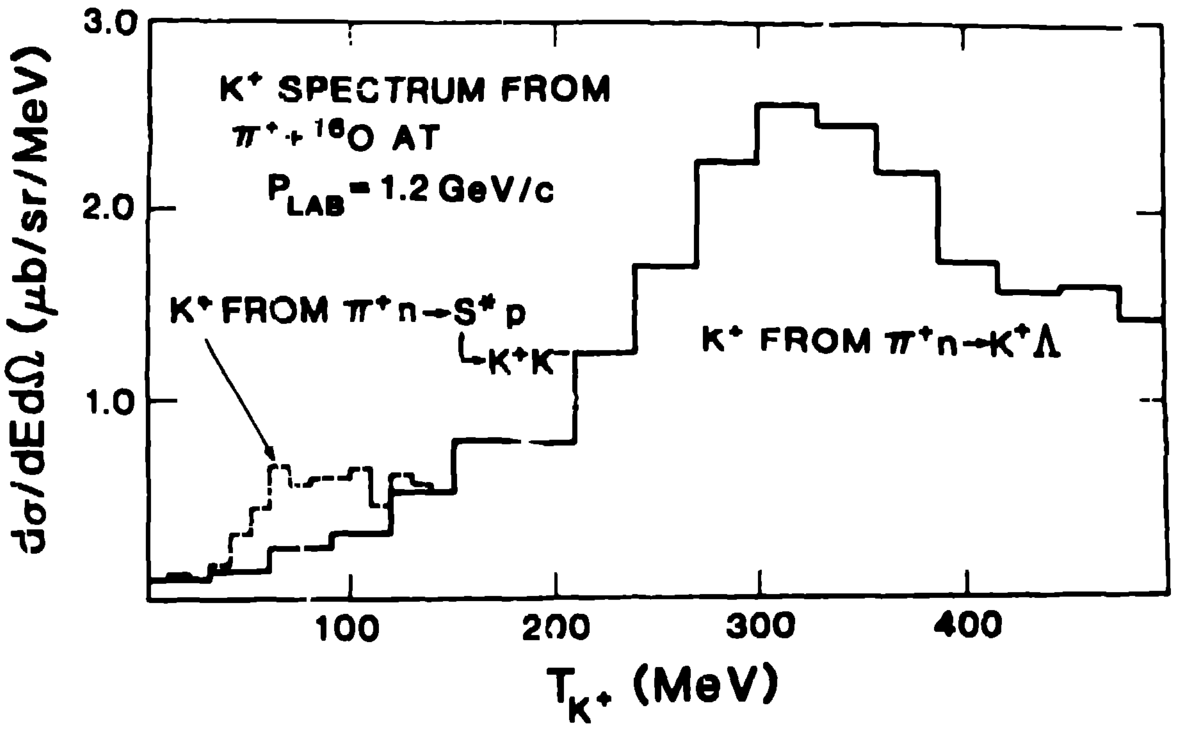

Figure 12. Histogram showing the K^+ spectrum from an S^* compared to the background from the $\pi^+ n \to K^+ \Lambda$ reaction.

We note that the present calculation is only indicative. Before proceeding much further we must take into account the fact that the S^* will decay, to some extent, before leaving the nucleus thus inducing an asymmetry in the K^+/K^- yield. We also need to look into the question of backgrounds from Σ production as mentioned above.

This work was supported by the U. S. Department of Energy.

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